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THE ION PAIR PRODUCTION FUNCTION OF THE LOWER IONOSPHERE

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ABSTRACT

Recent additions to the ionization mechanisms responsible for the lower ionosphere are reviewed. The acknowledged sources are:

1. Ionization of NO by solar Lyman alpha (1215.6A)
2. X-rays 2-8A acting on all constituents
3. Cosmic radiation

There remain uncertainties in the ion pair production function for nitric oxide and in the reaction of the D region to different 2-8A fluxes. For instance recently published NO airglow measurements of the nitric oxide distribution are inconsistent with X-ray enhancement effects.

Other processes which must be given consideration include:

4. Ionization of O_2 ($'\Delta_g$) by solar radiation $\lambda<1118A$
5. Ionization of NO_2 by solar Lyman alpha
6. Energetic electron precipitation
7. Fragmentation of water conglomerates by X-radiation

Their contribution to the total ion pair production function will be discussed. Experiments are suggested which should lead to a better understanding of the relative importance of the different ionization mechanisms.

Sources of ionization responsible for the formation of the lower ionosphere at night are also discussed.

1. INTRODUCTION

That portion of the ionosphere which falls below 100 km and comprises the D and lower E regions is the least understood part of the entire ionosphere. This is partly due to the inaccessibility of the region to all but sophisticated ground based measuring techniques and that only sounding rockets and not satellites can be used for in situ measurements. In addition the lower ionosphere is chemically the most complex region. It is not unusual for current theoretical models to involve 150 or more separate reactions in order to describe the distribution of ionized species.

The classical approach to the problem of the lower ionosphere is to first obtain an electron density profile such as shown in figure 1. Such a profile is explained on the basis of a combination of solar ultraviolet and X-ray sources and disociative recombination of electrons and positive molecular ions. Various ion-atom interchange and charge exchange processes occur as intermediates and the formation of negative ions is considered below 70 km during the day and 85 km at night. Between 85 and 100 km there is competition between photoionization of O_2 by Lyman beta at 1026.5A and 30-50A X-rays ionizing all constituents. In addition, meteoric ions are found on occasion. Below 85 km the D region is formed by photoionization of NO by Lyman alpha and background ionization by galactic cosmic radiation. Solar X-rays whose intensity varies greatly with solar activity can at times be the dominant source of ionization. The distribution of NO is determined by photochemical equilibrium. It is estimated to have a concentration of 2×10^{-8} n(M) where n(M) is the total neutral particle concentration.

As of mid 1969 the classical picture of the D region is being revised chiefly as a result of two measurements.

1. Determination of the nitric oxide density distribution by in situ spectroscopic measurements of the NO bands in the dayglow (Barth (1966) a,b, Pearce (1969)). The concentrations, 10^{-7} to 10^{-6} n(M), derived from these measurements necessitate an increase in the usually accepted values for the loss rates of electrons and ions.
2. Ion mass spectrometer measurements which showed that NO^+ was present in the D region as only a minor constituent, the majority of ions being hydrates such as H_3O^+, $H_5O_2^+$ and $H_7O_4^+$. Narcisi (1965, 1969), Goldberg and Blumle (1969).

This has led to a great deal of activity in the area of laboratory reaction rate studies, in situ measurements of positive ion densities, attempts to measure the species and number of negative ions and simultaneous measurements of solar ionizing radiations and D region electron densities. Factors which may affect the distribution of nitric oxide such as the temperature and pressure distribution within the mesosphere are also being given consideration.

In the abstract are listed the ionization mechamisms which have been proposed for the daytime lower ionosphere. The information available to determine the relative importance of the different sources will be reviewed in this paper as will those sources important at night. The origin of auroral and polar cap absorption events will not be considered.

2. NITRIC OXIDE AND THE FORMATION OF THE D REGION

The processes which control the distribution of NO were enumerated by Nicolet (1955). The model for computing NO employed by Nicolet and Aikin (1960) and Aikin et al (1964) utilized the reactions

$$N + O_2 \rightarrow NO + O \qquad b_1$$

and

$$N + NO \rightarrow N_2 + O \qquad b_2$$

with the final altitude distribution given as a fraction of the O_2 distribution 10^{-10} n(M) and 10^{-8} n(M) in the two cases. Such an assignment implies mixing and a long lifetime. More recently, Sechrist (1967) Mitra (1968, 1969), the temperature dependence of reactions b_1 and b_2 has been included in a precise way together with the reaction $N+O \rightarrow NO$ and the NO distribution has been predicted as a distribution which does not follow mixing but rather a strict photochemical behavior namely

$$n(nO) = 10^{-1} \exp(-3000/T)\, n(O_2) + 5 \times 10^{-7}\, n(O)$$

On this basis the NO distribution would be expected to reflect changes with temperature and atomic oxygen concentration in the mesosphere thus accounting for the anomalous winter MF absorption.

Dayglow observations have been conducted of the NO airglow gamma band ($A^2\Sigma^+ - X^2\pi$) Barth (1966a,b). The data shown in figure (2), curve III and points marked Barth. It has been proposed, Sechrist (1967) that the Barth measurement occurred at a time of enhanced mesospheric temperature and hence NO concentration. Recent correlative measurements, Pearce (1969), show this not to be the case. Geisler and Dickinson (1968) have pointed out that since the lifetime of NO is the order of weeks that photochemical or semiphotochemical approaches to the NO distribution problem are inadequate and that diffusion should be included in the calculation. Such a calculation has been carried out by Hestevedt and Janssen (1968). Their distribution is shown in figure 2,II. The density at 80 km is a factor of 6 less than the observed value. However, careful consideration should be given to the boundary conditions of this calculation. For instance the upper boundary is determined by the photochemical reactions

$$N + 0 \rightarrow NO + hv$$

$$N + NO \rightarrow N_2 + 0$$

$$NO + hv \rightarrow N + 0$$

$$N_2 0 + hv \rightarrow N_2 + NO$$

Ionic reactions such as those employed by Nicolet (1965) are not included. Norton (1967) has suggested that in the lower E region the reaction involving excited N namely $N(^2D) + 0_2 \rightarrow NO + 0$ must be included in addition to other ionic and chemical reactions.

The need for including transport processes has been further reinforced by the dayglow measurement carried out by Pearce (1969). The distribution he obtained is shown in figure 2, III. Mixing is clearly followed for this profile. Such large concentrations can only be explained by including transport terms. There is at present no quantiative explanation of the NO distribution. The wide range of possible NO profiles lead to a situation where the $q_{LY\alpha}$ can vary by 3 orders of magnitude depending on the nitric oxide concentration employed. Values of $q_{LY\alpha}$ are shown in figure 3 for the Barth and Pearce values of NO as well as an earlier value taken from Aikin et al (1964). The zenith angle is taken as 60^o.

3. NO_2^+ AS A CONSTITUENT OF THE D REGION

Photoionization studies of NO_2 show the ionization potential(IP) to be 9.75 ev Diebler et al (1967) and more recently 8.8 ev, Natalis and Collin (1968). Both these determinations of the ionization potential allow NO_2 present in the mesosphere to be ionized by the solar Lyman alpha line at 1216A as well as other wavelengths shorter than 1272 A for IP-9.75 ev and 1409A for IP-8.8 ev.

For wavelengths longer than 1369A the O_2 absorption cross section is (1-1.5) X 10^{-17} cm^2 so that radiation is absorbed above 100 km. Between 1369A and 1340A, the onset of NO ionization, the O_2 absorption cross section decreases to 2.2 x 10^{-18} cm^2. Nitrogen absorption is negligible throughout the wavelength interval, Watanabe (1958). In the case of NO Lyman-alpha is the dominant source of ionization. Therefore, it is reasonable to assume that NO_2 has an ionization cross-section equivalent to that for NO, 2 x 10^{-18} cm^2 regardless of which ionization potential is applied. The ion pair production function will be

$$q_{NO_2} = q_{NO} \frac{[NO_2]}{[NO]}$$

The distribution of NO_2 is considered to be determined by the processes, Nicolet (1955, 1965)

$$NO + O \rightarrow NO_2 + hv \qquad k_1$$

$$NO + O + M \rightarrow NO_2 + M \qquad k_2$$

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad k_3$$

$$NO_2 + hv \rightarrow NO + O \qquad J_{NO_2}$$

$$NO_2 + O \rightarrow NO + O_2 \qquad k_5$$

where the k's are rate coefficients and J_{NO_2} is the dissociation rate for NO_2. Under equilibrium conditions this gives

$$\frac{[NO_2]}{[NO]} = \frac{k_1[O] + k_2[O][M] + k_3\ [O_3]}{J_{NO_2} + k_5\ [O]}$$

A value of $[NO_2]/[NO] \sim 10^{-3}$ in the 70 to 85 km altitude region during the day is in good agreement with a complete computer solution of the equations by Keneshea and Fowler (1966). The usually quoted lifetime of NO_2 is 200 seconds and it will behave like ozone so that an increase will occur during the night and solar eclipses. At the end of the night the ratio $[O_3]/[O]$is 10^4 at 70 km and unity at 80 km. The $[NO_2]$density will exceed the NO density in the lower mesosphere. An exact solution of the equations involved should be undertaken for any thorough study of the nocturnal NO_2 distribution.

It is also possible that the reaction

$$NO^+ + NO_2 \rightarrow NO_2^+ + NO + 1eV$$

will occur if IP is indeed 8.8 ev. The rate coefficient should be in the 10^{-10} cm^3 sec^{-1} range. Because of the low concentration of NO_2 this reaction will probably have a small effect on the distribution of NO^+ during the day. NO_2^+ could be a constitutent of the nighttime D region. In fact Narcisi (1967) has reported observing 46^+ during a nighttime flight of a rocket borne ion mass spectrometer. The ion was not reported for any daytime flights. However, recently laboratory measurements have been carried out of the reaction

$$NO_2^+ + NO \rightarrow NO^+ + NO_2$$

Fehsenfeld et al (1969) who finds a rate coefficient of 2.9×10^{-10} cm^3 sec. This would indicate that the IP must be at least 9.25ev in agreement with Diebler et al (1967).

4. IONIZATION OF EXCITED O_2

There have been several suggestions that excited O_2 contributes to the ionization of the D region. Inn (1968, a, b) has considered the possibility that vibrationally excited O_2 is formed by the reaction sequence

$$O_3('A) + hv \rightarrow O_2('\Delta_g) + O('D)$$

$$O('D) + O_3('A) \rightarrow O_2(^3\Sigma_g^-)\ v > 11 + O_2(^3\Sigma_g^-)$$

The vibrationally excited O_2 would be ionized by Lyman alpha. A concentration 2×10^5 cm^{-3} was predicted. This could lead to $q^*_{O_2}$ of 10^{-1} for an assumed ionization cross section of $2 \times 10^{-18} cm^2$. The question has recently been reopened by Krassovsky (1969) who suggests 10^8 cm^{-3} based on OH emission. Vibrationally excited O_2 has never been detected in the mesosphere.

However, the existence of metastable $O_2(^1\Delta_g)$ is well documented (Noxon (1967) Evans et al (1968, 1969)),with recent determinations giving 3×10^9 cm^{-3} at 80 km. In addition it has been observed that this molecule can be ionized by radiation of wavelength $\lambda<1118A^o$. Assuming the ionization cross section to equal the absorption cross section for ground state O_2, Hunten and McElroy (1968) have calculated the production function shown in figure 3.

5. X-RAY EFFECTS

There is a wide variation in the intensity of 2-8A x-rays emitted by the sun. The most intense outbursts are associated with solar flares and are the origin of enhancements of D region ionization termed sudden ionospheric disturbances or SID's. There can also be X-ray enhancements which are not associated with any large events in the visible part of the spectrum. Some of these enhancements will lead to D region modification. The threshold flux necessary to cause a measurable change in the D region electron density will depend on the other sources of production for instance - the quantity of nitric oxide, and the ionization of $O_2(^1\Delta_g)$.

Figure 1 shows the result of several rocket measurements, of electron density under conditions of different x-ray fluxes. Curve 1, Aikin et al (1964), was obtained in 1963 under conditions of a completely quiet sun. Curves 2 and 3 are data obtained during the course of an x-ray enhancement event, on 16 January 1968, Somayajulu and Aikin (1969a) and curves 4 and 5 depict the electron density distribution during a class 1 solar flare of

21 August 1968, Somayajulu and Aikin (1969b). All flights were carried out from Wallops Island, Virginia. Table II lists the approximate zenith angle for each flight together with x-ray fluxes as determined by satellite. There is progressive enhancement of the electron density distribution with solar x-ray flux. Curve 1, which applies to low solar activity can be considered to be unaffected by x-rays. The production function corresponding to this case is shown in figure 3. The flux at that time was about 2×10^{-4}. Somewhere between 2×10^{-4} ergs/cm^2sec and 4×10^{-3} ergs/cm^2 sec is the threshold for D region X-ray effects at 60^o zenith angle. An influence of x-rays is apparent for the profiles labeled 10.275. The profiles are almost identical except there is a slight difference between the two curves at low altitudes, which is attributed to a softening of the x-ray spectrum. A decrease in intensity at short wavelength was observed by the proportional counter experiment aboard the OSO IV satellite and is evident in the 0.5 - 3A data of Table II.

An estimate of the production function for 10.273 is given in figure 3. It is approximately the same as the q_{NO} which would be derived for Barth's NO concentrations. The q x-ray III applies to 14.369 and this q is slightly larger than the q which applies for the Pearce NO values. X-ray q values will be refined when data from proportional counter included on the rockets is reduced. This will give us the exact number of photons/cm^2 sec in a particular wavelength interval arriving at each altitude.

While it is certain that 4×10^{-3} ergs/cm^2 sec will show a D region effect, the minimum flux necessary has not yet been established. For instance Bowling et al (1967) have reported that during the annular solar eclipse of May 20, 1966, the covering and uncovering by the moon of X-ray emission regions produced observable changes in the ion density distribution of the D region. At the time of the 20 May eclipse the 2-8A flux was 4.5×10^{-4} ergs/cm^2 sec thus giving q's only somewhat larger than the completely quiet sun case, curve X-ray I of figure 3. Except for the time of residual x-ray flux during maximum observation the larger q_{NO}'s will dominate. The $q_{O_2}{}^{*}$ will also be larger although asymmetric with respect to totality due to the changes in $O_2(^1\Delta_g)$ during the eclipse. Although the validity of Bowling et al's conclusions have been questioned by Kane (1969), more eclipse studies of the relationship between x-rays and electron and ion density changes should be conducted. Additional correlations of x-ray flux with electron density profiles are also needed.

6. COSMIC RADIATION

Galactic cosmic radiation is an important factor in the formation of the lower D region and was considered in relation to other sources of radiation by Nicolet and Aikin (1960) and Mohler (1960). If $q_0(\emptyset)$ is the ionization rate for $n_0 = 2.6 \times 10^{19}$ molecules cm^{-3} at geomagnetic latitude $\emptyset$ then the ionization rate for a number density n is

$$q(\emptyset) = q_o(\emptyset)\ n/n_o\ \text{cm}^{-3}\ \text{sec}^{-1}$$

Van Allen (1952) has shown that $q_o(\emptyset)$ is reduced by a factor of

10 at the geomagnetic equator compared to a latitude of 70^{o}, namely between 30 and 300 ion pairs cm^{-3} sec^{-1}. Evidence for a corresponding effect on the lower ionosphere has been demonstrated by Bragin (1967) by means of a series of ion density profiles for different latitudes. The variation with latitude and solar cycle has been summarized by Webber (1962) and the results of his calculations shown in figure 3 for sunspot minimum and maximum where the geomagnetic latitude is 50^{o}. The important factor to bear in mind is that $q_o(\emptyset,Z)$ is a factor of 2 larger at sunspot minimum compared to sunspot maximum.

7. ENERGETIC ELECTRONS

Several investigators have indicated that electron precipitation into the mesosphere exists at middle and low latitude. O'Brien et al (1965) carried out measurements at Wallops Island 39^{o} N L = 2.5. More recently a latitude survey was conducted by Tulinov et al (1968). For an altitude of 87 km the number of electrons E > 50 Kev observed as a function of the McElwain L value is shown in figure 4.

The measurements were made over a period of years and hence there is no information on the time history of the precipitation. Tulinov and Yakovlev (1969) have calculated the contribution that such particle fluxes would make to the ion-pair production function of the D region. Their result is shown in figures 3 and 5. It is estimated that for midlatitudes the q for electrons is about 2×10^{-1} cm^{-3} sec^{-1} at 80 km.

If particle precipitation is a dominant source of ionization then one would expect a latitude variation to the electron density distribution. Such a variation has been reported by Mechtly et al.(1969). However, their results shows the inverse of what one would expect on the basis of the results displayed in figure 4.

Gurnett (1968) has reported VLF hiss at L=1.1: The source of this hiss is usually attributed at high L values to plasma instability for particles with energy greater than 50 Kev. Whether a precipitation of 50 Kev or greater particles at equatorial latitude is implied by this measurement or if some new wave generation mechanism is involved is unknown at present.

There is strong evidence for particle precipitation at L values above 3. Direct measurements of electrons precipitation correlated with absorption studies have been reported by Maehlum (1967). The combination of particle precipitation and seasonal variations of solar altitude have been proposed as one of the sources of the "winter anomaly" in ionospheric absorption. Belrose and Thomas (1968) have shown that ionization increases following magnetic storms. Bourne and Hewitt (1968) report a dependence of MF radio absorption on the Kp index.

8. SOURCES OF NIGHTTIME IONIZATION

There exists a nocturnal electron density distribution in the lower ionosphere, which exceeds that expected on the basis of a simple decay of the daytime ionosphere. The maximum density is between 10^3 and 10^4 cm^{-3} and is centered at an altitude of 105 km where a layer of one scale height thickness occurs, (Aikin and Blumle (1968)). At midlatitudes sporadic E is often superimposed.

Several workers have discussed the role of scattered solar Lyman alpha acting on NO as the ionization source, Swider (1965), Ogawa and Tohmatsu (1966), Nicolet (1965) Radicella (1968). For an intensity of 4 kR and the Pearce distribution of NO the ion pair production function has the form given in figure 5.

The influence of scattered Lyman beta has been suggested by Swider (1965) and detailed calculations have been carried out by Ogawa and Tohmatsu (1966). Their result is shown in figure 5 and Lyman beta is the dominant source of ionization above 95 km. Electron impact excitation of atomic oxygen above 200 km will prodice radiation at 1304 A. Photons of this wavelength are capable of ionizing NO, however their effect may already have been included in measurements of scattered Lyman alpha since the bandwidth of the detectors is 1050 - 1340A. Radiative recombination of atomic oxygen ions will give photons which can ionize O, and O_2. The intensity of this radiation is unknown at present.

Recently, there have been reports of the influence of the galactic x-ray source Sco-XR-1 on long distance VLF propagation, Edwards et al (1969). These authors calculate a q of $5 \times 10^{-3} cm^{-3} sec^{-1}$ for the XR-I source which will be dominate if n(NO) does not exceed 5×10^{-6} [M] cm^{-3} and with a scattered Lyman alpha intensity of 1kR.

Cosmic radiation and energetic electrons will also be nighttime sources and these are shown in figure 5.

CONCLUSIONS

There exists a great uncertainty in the ion pair production function of the lower ionosphere. This is particularly the case with regard to the production function resulting from the ionization of NO. The recent measurements of the mesospheric distribution of nitric oxide lead to large values of the production function which will obscure ion pair production due to other sources such as cosmic rays, x-ray flares, and precipitated electrons. In order to accommodate all the information it is necessary to have a major revision in the concepts of loss processes which are operative in the formation of the lower ionosphere and to consider that one species of ion may be more important than another even though it is created in lesser amounts.

However, before such extensive modifications are made to the theory of the lower ionosphere, it is necessary to critically examine the data on the new parameters such as nitric oxide and ion composition. For instance, in the case of nitric oxide flourescense there are problems of absolute calibration of the detector - system and the effect of atmospheric Rayleigh scattering. For rocket measurements of ion composition there are the unknown factors of modification of ion species during collection and outgassing of the rocket body. Also many necessary experiments have not been carried out. Examples of such experiments include:

1. Independent verification of the nitric oxide density distribution
2. Detailed correlation of solar x-ray flux variations with lower ionosphere properties such as electron and ion density and ion composition
3. Simultaneous measurements of precipitated electron fluxes and lower ionosphere properties

4. More investigations of the behavior of the lower ionosphere during eclipses.
5. Further studies of the nighttime lower ionosphere and the sources which affect it

Only in this way can a quantative description of the lower ionosphere and the source of ionization responsible for it be obtained.

TABLE I

Rocket	Solar Zenith Angle	X-ray 0.5 - 3A	Flux ergs/cm^2/sec 1-8A
14.107	53^{o}		1.9×10^{-4}
10.273	65^{o}	4.5×10^{-5}	5.8×10^{-3}
10.275	68^{o}	1.4×10^{-5}	3.9×10^{-3}
14.369	42^{o}	1.2×10^{-3}	9.0×10^{-2}
14.368	42^{o}	5×10^{-4}	2.5×10^{-2}

FIGURE CAPTIONS

Figure 1 - Electron density profiles for different incident X-ray fluxes

Figure 2 - Distributions of nitric oxide I Aikin et al (1964) II Hestevedt and Janssen (1968), III Pearce (1969) Barth (1966).

Figure 3 - Daytime sources of ionization as described in the text.

Figure 4 - Measurements of energetic electrons E > 40 kev as a function of L value after Tulinov and Yakovlev (1969)

Figure 5 - Nighttime sources of ionization as described in the text.

TABLE CAPTIONS

Table I - X-ray fluxes and solar zenith angles at the time of different rocket firings

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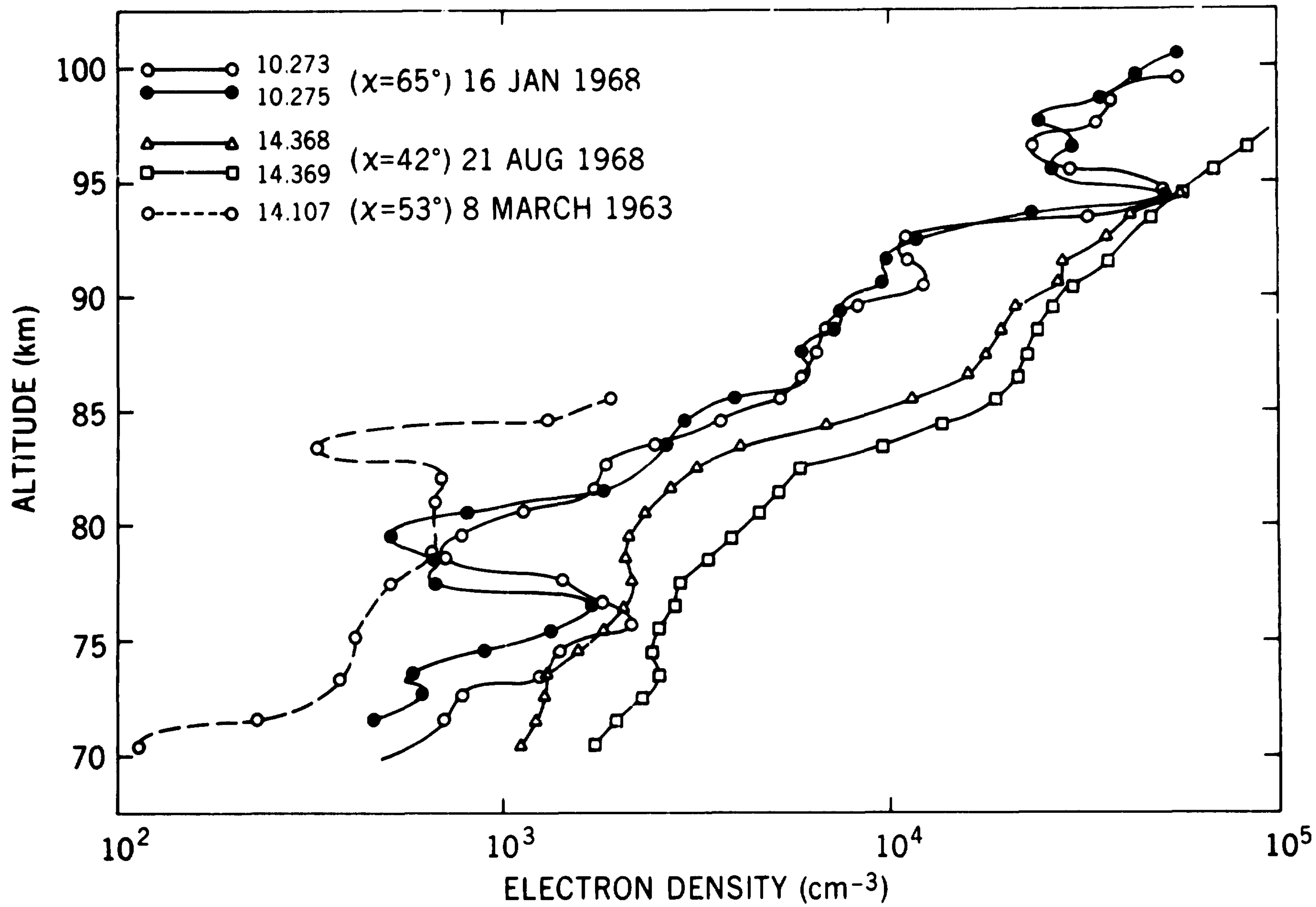

Figure 1 - Electron density profiles for different incident X-ray fluxes

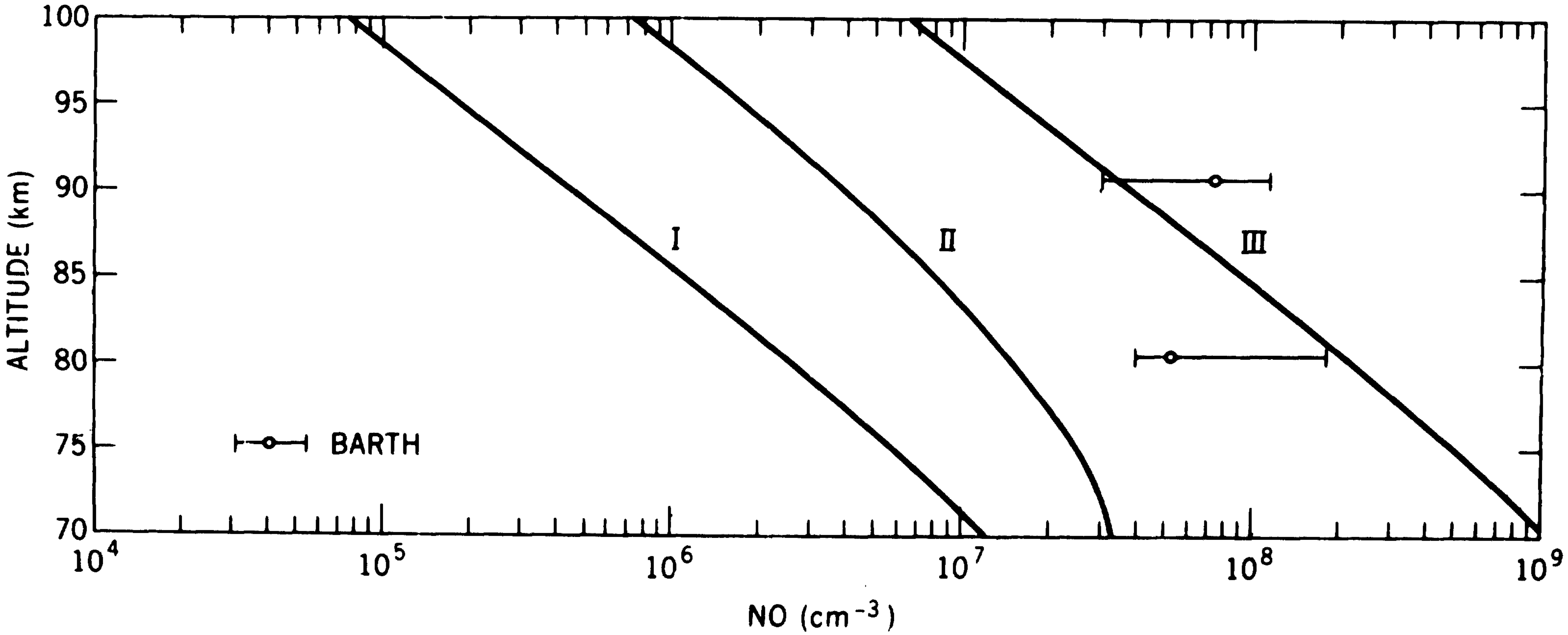

Figure 2 - Distributions of nitric oxide I Aikin et al (1964) II Hestevedt and Janssen (1968), III Pearce (1969) Barth (1966)

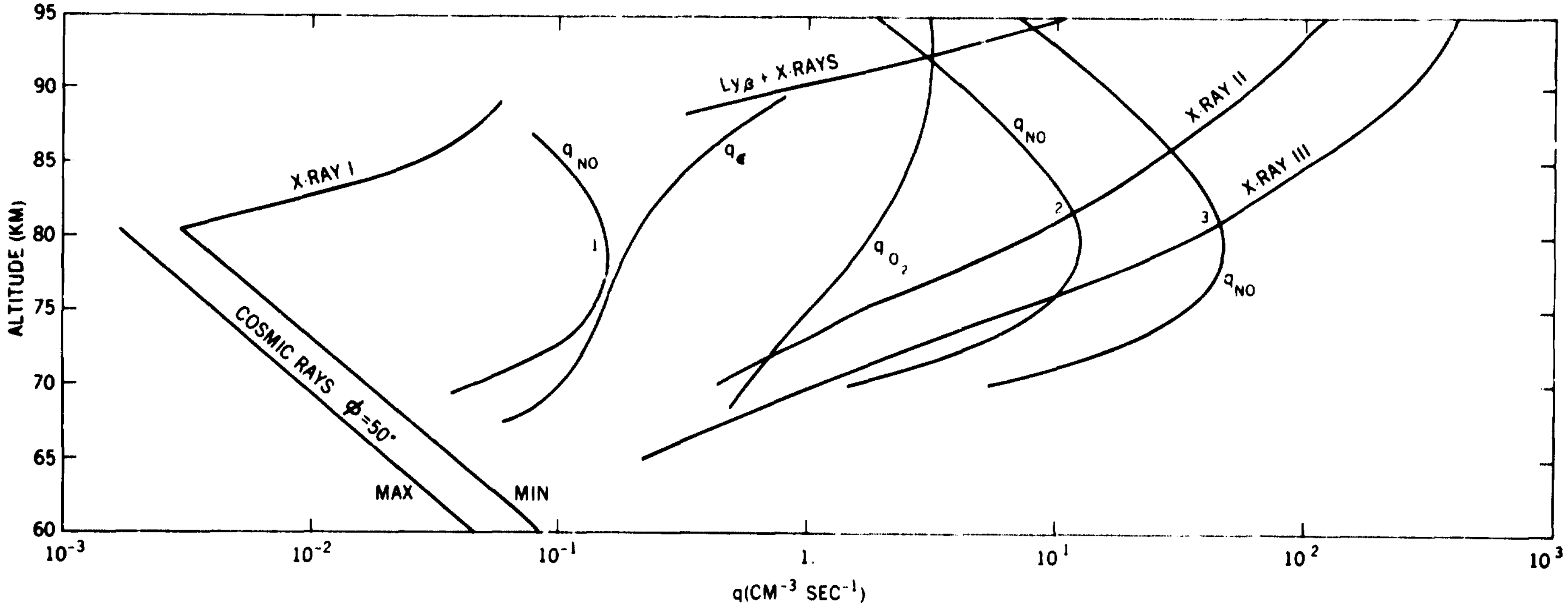

Figure 3 - Daytime sources of ionization as described in the text

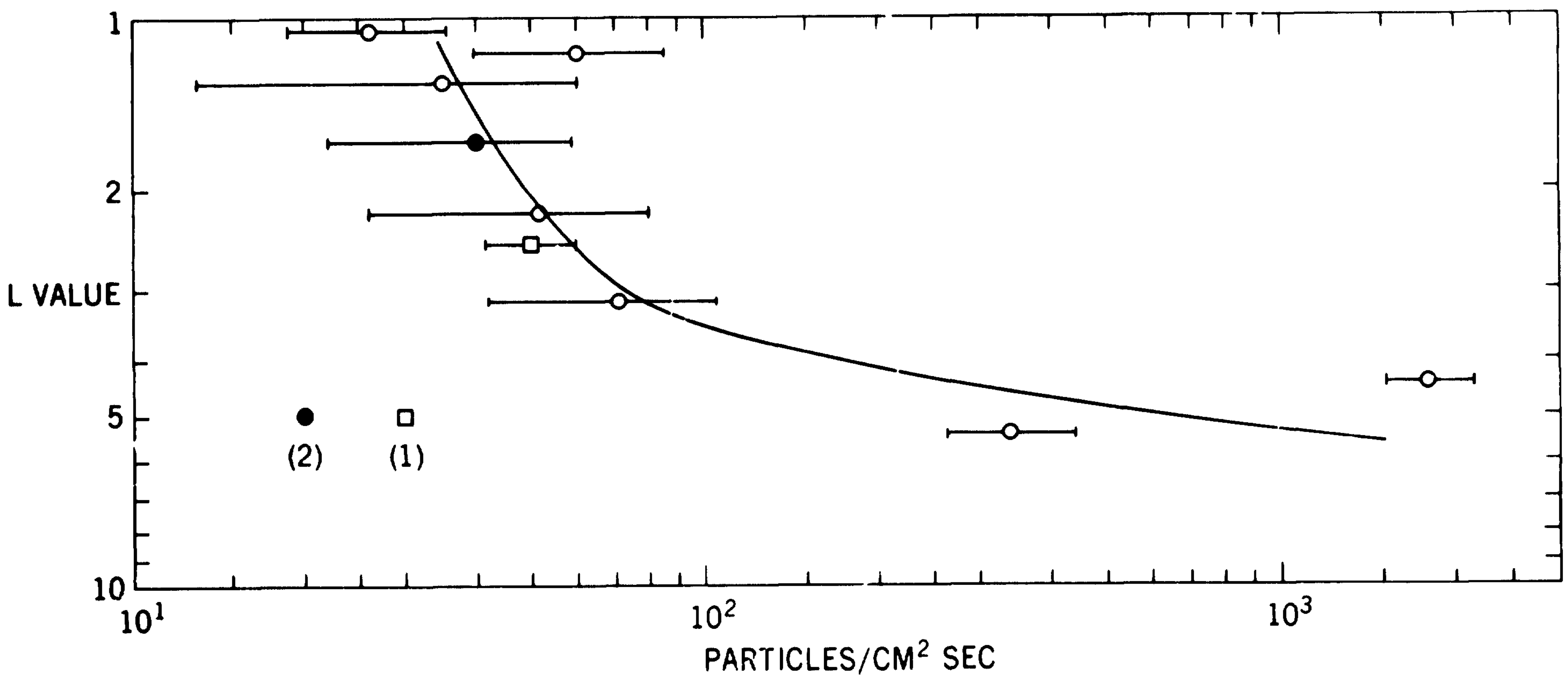

Figure 4 - Measurements of energetic electrons E > 40 kev as a Function of L value after Tulinov and Yakovlev (1969)

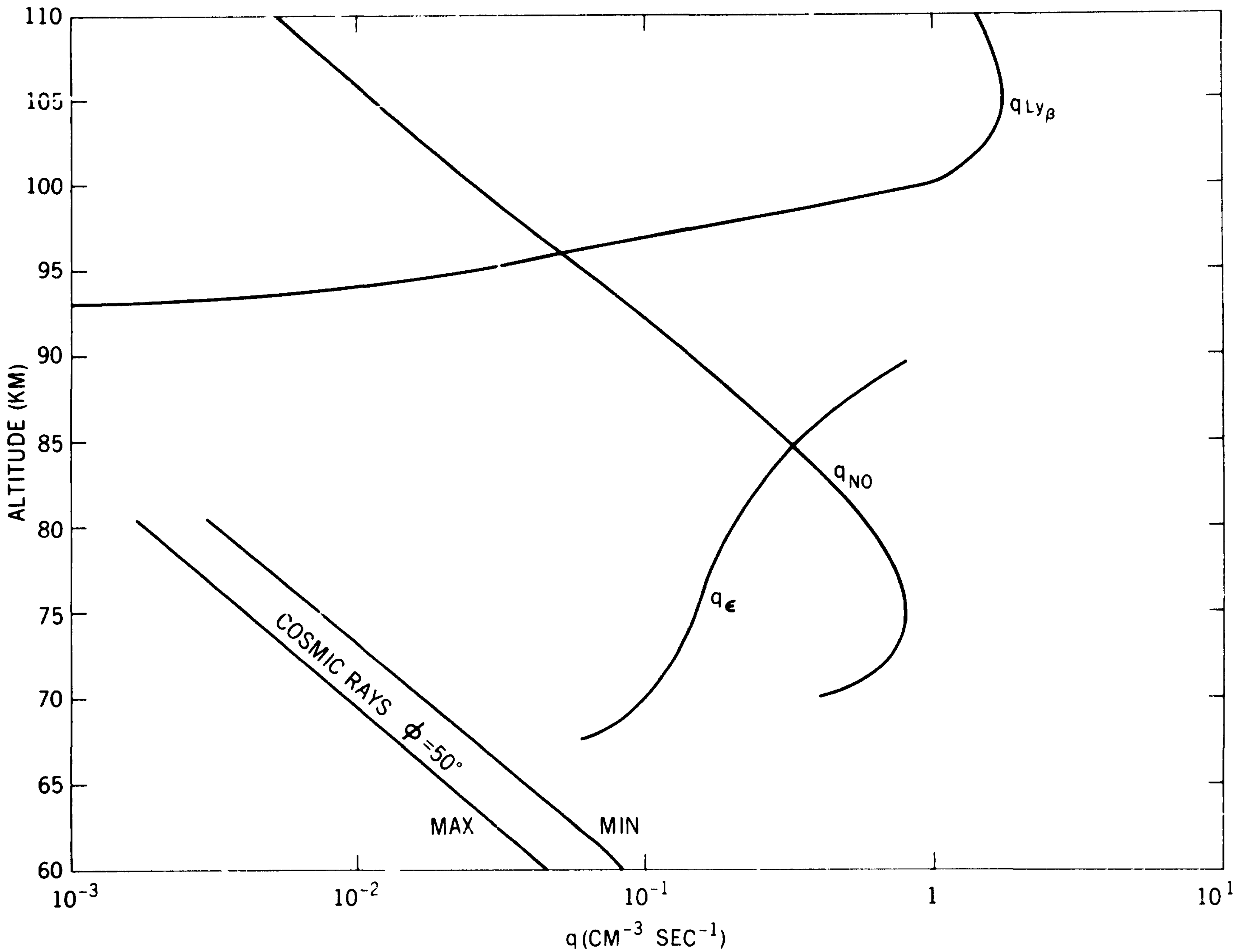

Figure 5 - Nighttime sources of ionization as described in the text